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STATISTICAL SUMMARY AND EVALUATION OF VENTOELECTRIC POWER STATION OUTPUT (PART 2 OF 2)

D. R. Stein

Translation of "Statistiche Erfassung und Auswertung der Energieerzeugung von Windkraftwerken," Elektrizitätswirtschaft, Vol. 50, No. 11, Nov. 1951, pp. 325-329

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16. Abstract (Second of two parts) Data obtained from the operation of windmills in Denmark are used to study the performance of several sizes and designs. Tabulated information shows how performance is affected by wind velocity patterns, particularly mean velocities, by rotor diameter and by how the output is used; what fraction of available wind is utilized; how regularly or irregularly output varies with time; what peak values occur; the duration of lulls; and how utilization time depends upon the power level which is used as a reference.

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STATISTICAL SUMMARY AND EVALUATION OF VENTOELECTRIC POWER STATION OUTPUT (PART 2 OF 2)

Dimitri R. Stein

Conclusion from Previous Issue /325*

Of the questions posed in the introduction, question (1a), that of the output of a ventoelectric power station of given dimensions and of a given design as a function of its particular mode of operation, was answered in the first part of this article for conditions in Denmark. It now remains to answer (1b), how output depends upon average wind conditions, in order to compile valid empirical data for the output of ventoelectric power stations. Question 2, as to what percentage of available wind is exploited in practical terms in the systems covered, must then also be answered and the results obtained must be extended to other average wind conditions.

b. Significance of Average Wind Velocities

On the basis of meteorological studies, we can expect a yearly average wind velocity of 5 to 6 m/s above the ground in Denmark. At the level of the wind rotor, a value of 6 m/s will therefore be assumed for further discussion. The frequency of various wind velocities must now be determined in order to establish the theoretical availability of wind. Applicable curves of wind frequency for various mean wind velocities have been developed by several authors [1-3] on the basis of theoretical considerations and empirical results. These numerical data given by the different authors for the duration of given wind strengths during the course of a year do not deviate appreciably from one

* Numbers in the margin indicate pagination in the foreign text.

another. An exact study of these problems (which would exceed the scope of this article) would be very valuable for all considerations concerning wind energy.

König's data, which lie approximately at the center of the range of values given by the other authors and probably are closest to actual conditions, will be assumed for further discussion. Accordingly, the frequencies of wind velocities from 3.5 to 10.5 m/s, which primarily come under consideration for exploitation by ventoelectric plants, are compiled in Table 3 for yearly mean wind velocities of V = 6, 5 and 4 m/s (from König). /326
Available energy is then determined from this, assuming a constant power coefficient and constant losses ($c_1 \cdot \eta_{trans} \cdot \eta_{gen} = const$), on the basis of the applicable power and duration for the wind rotor diameters specified. This assumption involves a simplification, but one which is adequate for a good approximation in this regard. The possible energy outputs are then compiled in Table 4 for the various yearly mean wind velocities, based on the values calculated in Table 3, and the corresponding percentages are determined. The value for v_m = 4.5 m/s has been obtained here by graphic interpolation.

In considering these percentages, we are struck by the fact that the quantity of energy available does not increase as rapidly with yearly mean wind velocity as could be expected on the assumption of a cubic rise in power. This phenomenon occurs because wind velocities ranging from 3 to 10 m/s come under consideration for economic exploitation by ventoelectric power plants of the general size described. At higher v_m, a larger and larger percentage of the winds already lies above this limit and is either utilized under poor conditions or not at all. Even winds of 8 to 10 m/s, lying just under this limit, frequently cannot be fully exploited in individual and local power supply

TABLE 3. DETERMINATION OF POSSIBLE OUTPUT OF AN 18-m VENTOELECTRIC POWER PLANT, BASED ON THEORETICAL WIND DISTRIBUTION

Wind velocities m/s	3,5-4,5	4,5-5,5	5,5-6,5	6,5-7,5	7,5-8,5	8,5-9,5	9,5-10,5	Total
Hours/year at $v_m = 6$ m/s	1120	1080	1060	900	750	610	438	5858
Hours/year at $v_m = 5$ m/s	1320	1260	1050	840	582	392	242	5686
Hours/year at $v_m = 4$ m/s	1580	1220	915	540	307	150	66	4358
$c_1 \cdot \eta_{tot}$ [1]	0,3	0,3	0,3	0,3	0,3	0,3	0,3	—
Generator power kW	3,0	5,8	10,0	16,0	23,7	34,1	46,5	—
Possible output at $v_m = 6$ m/s kWh	3360	6270	10600	14400	17760	20800	20400	93590
Possible output at $v_m = 5$ m/s kWh	3960	7300	10500	13400	13800	13350	11250	73560
Possible output at $v_m = 4$ m/s kWh	4680	7080	9150	8640	7280	5120	3070	45020

[1] c_1 = power coefficient of wind rotor;
η_{tot} = total efficiency referred to generator power

TABLE 4. POSSIBLE OUTPUT OF AN 18-m VENTOELECTRIC POWER PLANT FOR VARIOUS WIND VELOCITIES CORRESPONDING TO THEORETICAL WIND DISTRIBUTION

Yearly mean wind velocity v_m m/s	Possible output, from Table 3 kWh	Possible output, referred to 6 m/s %
6	93 590	100
5	73 560	79
4,5	59 800	64
4	45 020	48

systems, since they usually occur in gusts and once the storage batteries are charged, suitable consumption often does not occur.

Table 5, in which the utilizable quantity of energy from ventoelectric power plants of various designs with rotor diameters of 12 to 24 m is compared for various operating and wind conditions, has been derived from actual generating values for Denmark (Table 2), taking the percentages calculated from Table 3 and 4 for various mean wind velocities into consideration. This compilation thus possesses general applicability, independently of Danish conditions, and takes the various designs[1], modes of operation and wind conditions into consideration. It represents the answer to the first of the questions presented at the beginning, which is of basic importance in the proper planning and designing of ventoelectric power plants.

The numerical material which has so far been collected and evaluated can now also be used as the basis for answering the additional questions formulated at the beginning. Upon determining the output which can actually be utilized, we are interested in the following:

2. What Portion of the Available Wind Is Exploited in Practical Terms?

The answer to this question is shown in Table 6. As can be seen, the full utilization of available wind by the ventoelectric power plants studied is in agreement for the various general sizes under the applicable operating conditions. About 31 to 40% of available wind is converted into electrical energy and delivered in usable form in the case of individual power supplies, 50 to 70% in the case of local power supplies, and even 71 to 100%

[1] The corresponding data for power plants with a u/v of 5 to 6 can easily be calculated by reasonable interpolation.

TABLE 5. UTILIZABLE OUTPUT OF VENTOELECTRIC POWER PLANTS OF VARIOUS DESIGN WITH ROTOR DIAMETERS OF 12 TO 24 m, FOR VARIOUS WIND AND OPERATING CONDITIONS, BASED ON DANISH EMPIRICAL DATA

Rotor diameter	Design	Operation[1]	Utilizable output at yearly mean velocity v_m (m/s) of 4	4.5	5	6
12	Medium speed u/v = 3 to 4, 4 blades	I	5 280	7 050	8 700	11 017
		L	7 380	10 050	12 400	15 719
		T	13 700	18 200	22 500	28 569
14	"	I	7 200	9 600	11 850	14 994
		L	10 350	13 800	17 050	21 588
		T	14 550	19 400	24 000	30 342
16[2]	"	I	—	—	—	—
		L	14 550	19 400	24 000	30 339
		T	—	—	—	—
18	"	I	9 300	12 400	15 300	19 393
		L	17 350	23 100	28 600	36 150
		T	25 500	33 700	41 600	52 670
17,5	High speed u/v = 7 to 9, 2 blades	I	12 350	16 500	20 300	25 760
		L	21 200	28 200	34 800	44 101
		T	35 100	46 800	57 750	73 122
24	High speed u/v = 5 to 7, 3 blades	I	—	—	—	—
		L	55 800	74 500	92 000	110 390
		T	—	—	—	—

[1] I = individual power supply, L = local power supply, T = parallel operation with long-distance transmission system (see text).

[2] Few reliable output data are available for this size.

in the case of parallel operation with the long-distance transmission system. For the Lykkegaard plants, the percentages are referred to a c_1 of 0.20. These results are very informative. They show that, on the average, ventoelectric power plants associated with individual or local power supplies utilize only 1/3 to 1/2 of the available energy. I.e. more efficient utilization of the wind and thus an increase in economy can only be achieved through an improvement in operational organization. /327 This result particularly emphasizes the importance of proper planning and design of ventoelectric power plants when they are set up.

It can be seen from Table 6 that in parallel operation with the transmission system, almost all wind energy which occurs can be

TABLE 6. QUANTITIES OF ENERGY UTILIZED AND AVAILABLE FROM EXISTENT WINDS FOR VENTOELECTRIC POWER PLANTS OF VARIOUS DESIGN WITH 12 to 24 m ROTOR DIAMETERS, FOR VARIOUS OPERATING CONDITIONS, BASED ON DANISH EMPIRICAL DATA

Rotor diameter	Design	Operation	Utilized (a) and available energy for v_m = 6 m/s and power coefficient of (b) c_1 = 0.2 and (c) c_1 = 0.3			Utilization of available wind, in %, for	
m			a	b	c	b	c
12	Lykkegaard, u/v = 3 – 4, 4 blades	I[1]	11 017	27 800	41 600	40	27
		L	15 719	27 800	41 600	56	38
		T	28 569	27 800	41 600	100	69
14	"	I	14 994	37 800	56 500	40	27
		L	21 588	37 800	56 500	57	38
		T	30 342	37 800	56 500	71	54
16[2]	"	I	—	—	—	—	—
		L	30 339	51 400	75 800	59	41
		T	—	—	—	—	—
18	"	I	19 393	62 500	93 500	31	21
		L	36 150	62 500	93 500	58	39
		T	52 670	62 500	93 500	84	56
17.5	F. L. Smidth, u/v = 7 – 9, 2 blades	I	25 760	—	88 500	—	29
		L	44 101	—	88 500	—	50
		T	73 122	—	88 500	—	83
24	F. L. Smidth, u/v = 5 – 7, 3 blades	I	—	—	166 000	—	—
		L	116 590	—	166 000	—	70
		T	—	—	166 000	—	—

[1] I = individual power supply, L = local power supply, T = parallel operation with long-distance transmission system (see text).

[2] Few reliable output data are available for this size.

made use of and thus the best utilization and highest economy can be achieved. In the F. L. Smidth plants with a rotor diameter of 24 m, wind utilization does not reach such high values because developmental problems had to be overcome in the operation of these plants and, in addition, the available transmission system could not accept all of the energy produced.

3. How Uniform is Output Over Relatively Short and Long Time Intervals?

In answering this question, we must distinguish between seasonal fluctuations in wind strength and daily variations in winds. Seasonal wind variations are fairly regular and can generally be characterized. Figs. 4 and 5, which were derived from the evaluation of a large number of similar ventoelectric power plants, show this quite clearly. In the summer months of June, July and August, output drops below the mean; it rises above the mean during the winter months. The differences on both sides amount to about 30% at the Lykkegaard power plants studied. At the F. L. Smidth power plants, wind conditions affect output a great deal more, as has already been explained elsewhere. The corresponding upward and downward variations amount to more than 50%. Nevertheless, the yearly output averages are practically constant within narrow limits for all of the power plants studied. At the 21 large Lykkegaard power plants which are covered, for example, output deviates by a maximum of +4 and -5% from the average during the years 1941 to 1944. The regularity of output over relatively long time intervals is thus appreciable and can be determined from the outset. This condition is of course necessary for the general validity of Tables 2 and 5.

A criterion for monthly fluctuations in output is the above-mentioned yearly extreme, which relates the monthly high and low output data for one year. The corresponding values are listed in Table 7. As was to be expected, the yearly extremes for the different Lykkegaard plants are similar, even though relatively large fluctuations occur. They reach appreciable values for the F. L. Smidth power plants, indicating the pronounced differences in output for the various months.

In addition to the seasonal wind fluctuations, which must be taken into consideration from the outset during planning, there

TABLE 7. YEARLY EXTREMES FOR DANISH VENTOELECTRIC POWER PLANTS OF VARIOUS DESIGNS WITH 12 TO 24 m ROTOR DIAMETERS, 1941 TO 1944

Rotor diameter m	Design	1941	1942	1943	1944	Mean
12	Lykkegaard, u/v = 3 → 4 4 blades	2,7	1,5	3,5	3,1	2,7
14	"	—	2,6	3,3	2,8	2,6
16	"	2,1	2,4	3,3	1,9	2,4
18	"	2,3	2,2	3,7	3,7	2,7
17,5	F. L. Smidth u/v = 7 → 9 2 blades	—	2,1	3,6	5,1	3,6
24	F. L. Smidth u/v = 5 → 7 3 blades	—	—	2,9	5,9	4.4

are also the daily variations in wind, which can hardly be predicted. The daily output of the Kølstrup ventoelectric power plant (18 m rotor diameter) for the year 1943, given in Fig. 6, is typical of this. Patterns cannot be detected here. Evaluation in terms of the duration of lulls and peak outputs is undertaken below.

4. What Peak Values Occur?

The corresponding maximum outputs achieved in one day are listed in Table 8 for the years 1943 and 1944 for various ventoelectric power plants. The minimum continuous power for which the electrical portion of the power plant must thus be designed has been calculated from the daily output data. /328

5. How Long Is Lull Time, On the Average?

The answer can be seen from the characteristic daily results for the Kølstrup power plant described above (Fig. 6). No appreciable lulls occurred in the months from January

TABLE 8. PEAK OUTPUT VALUES AND ASSOCIATED CONTINUOUS POWER LEVELS FOR VENTOELECTRIC POWER PLANTS OF VARIOUS DESIGN WITH 12 TO 24 m ROTOR DIAMETERS, BASED ON DANISH EMPIRICAL DATA

Rotor diameter m	Design	Output kWh/day		Cont. power kW		Associated wind velocity (m/s)	
		1943	1944	1943	1944	1943	1944
12	Lykkegaard, u/v = 3 – 4, 4 blades	218	154	9,1	6,4	8,6	7,7
14	"	305	391	12,7	16,3	7,8	9,6
16	"	434	389	18,1	16,2	9,1	8,5
18	"	637	578	26,5	24,1	9,7	9,2
17,5	F. L. Smidth, u/v = 7 – 9, 2 blades	1215	1209	50,4	50,4	10,4	10,4
24	F. L. Smidth, u/v = 5 – 7, 3 blades	1325	1358	55,2	56,6	8,8	8,9

through April. During the summer months, on the other hand, considerable lulls (about 8 days) can be found, during which output hardly reaches notable levels. Lulls also appear in the autumn and winter months. Of course, the output that reflects wind conditions for the power plant studied here does not have a regular distribution pattern; yet it can be considered characteristic of daily output, at least in principle, if not in its breakdown over time.

6. Utilization Time at Mean and Design Power

In general, we consider utilization time to be that time during which a quantity of energy is delivered or utilized. If, as is usual, we assume a maximum yearly utilization time of 8760 hours, the actual utilization time of a power plant must be below this value. The more efficient utilization is, however, the closer utilization time approaches the optimum value.

A problem occurs in determining the utilization time of ventoelectric power plants, however. While reference power --

either the peak load which occurs or installed power -- can generally be determined unequivocally, it is necessary to agree upon which power is to be used for determining utilization time in the case of ventoelectric power plants, since operating power continually fluctuates as a function of wind conditions at such plants. An unequivocal measurement of the power associated with a particular wind velocity is difficult in technical terms, since instantaneous wind velocities in the free air current cannot be determined clearly, even when several anemometers are applied. The installed power of the systems (i.e., the magnitude of output) can usually not be taken as the proper bases for determining utilization time, since the systems are designed very differently; design is a function of local operating and wind conditions, and therefore does not provide a possibility for comparison. If a wind velocity is chosen, incorrect pictures are likewise often obtained, due to the differences in design.

Utilization time at mean and nominal power is calculated in Table 9 for the Danish ventoelectric power plants studied, taking these aspects into consideration. Mean power is assumed at v = 7 m/s and nominal power at v = 10 m/s. Such a rating pattern also corresponds to models used to date, which are usually designed for 7 m/s in German systems and generally for 10 m/s in Danish systems. The corresponding associated power is determined mathematically, making use of the individual efficiencies and power coefficients, which deviate for various wind velocities.

The values for v = 7 m/s are particularly characteristic for evaluation, since more and more firms have recently been designing their systems for this wind velocity. This design also corresponds to a maximum utilization of energy at mean wind conditions. As can be seen, utilization time for the Lykkegaard plants with rotor diameters of 12 to 18 m fluctuates here between 3300 and 3600 hours for local power supply. Utilization of the

TABLE 9. UTILIZATION TIME AT MEAN AND NOMINAL POWER FOR VENTOELECTRIC POWER PLANTS OF VARIOUS DESIGN WITH 12 TO 24 m ROTOR DIAMETERS, BASED ON DANISH EMPIRICAL DATA

	Operation[1]	Rotor diameter (m) Type: Lykkegaard 12	14	16	18	F. L. Smidth 17,5	24
Energy delivered kWh	I L T	11 017 15 719 28 569	14 994 21 588 30 342	— 30 339 —	19 393 36 150 52 670	25 760 44 101 73 122	— 116 390 —
Power[2] (kW) at v =	7 m/s 10 m/s	4,76 10,34	6,47 14,10	8,40 18,37	10,60 23,22	15,2 36,8	28,5 69,1
Utilization time at v = 7 m/s h	I L T	2 320 3 320 6 020	2 320 3 330 4 680	— 3 610 —	1 830 3 410 4 970	1 815 2 900 4 810	— 4 080 —
Utilization time at v = 10 m/s h	I L T	1 066 1 520 2 760	1 062 1 530 2 150	— 1 654 —	786 1 555 2 260	700 1 196 1 985	— 1 685 —
Theoretical power[3] (kW) at v_1 = 7 m/s		14,06	19,09	24,75	31,25	29,90	56,10
Theoretical utilization time at v = 7 m/s h	L	1 125	1 129	1 227	1 158	1,476	2 075

[1] Operation: I = individual power supply, L = local power supply, T = parallel operation with long-distance transmission system

[2] Assumed efficiencies: at v = 7 m/s — 10 m/s

$c_1 \cdot \eta_{trans} \cdot \eta_{gen}$ = 0.20 — 0.15 (Lykkegaard plants)

= 0.30 — 0.25 (F.L. Smidth plants)

[3] $c_1 \cdot \eta_{trans} \cdot \eta_{gen} = 0.59$

F. L. Smidth plant with a diameter of 17.5 m is only 2900 hours, due to a design improperly based on excessive wind speeds; that of the modern, well-designed F. L. Smidth plant with a diameter of 24 m is 4100 hours. These values are still very informative, since they considerably exceed the utilization time of 1500 hours still reported by specialists in recent times for such conditions.

The utilization times of the different ventoelectric power plants, which vary regardless of the wind conditions that occur,

are functions of design and of the resultant coefficients and efficiencies, and make it difficult to compare the different systems with regard to utilization of the wind. In order to make this problem clearer, theoretical rotor power is also determined in Table 9, based on a maximum lossless utilization of the kinetic energy of the free wind current corresponding to diameter, and theoretical utilization time is calculated from actual energy output, permitting comparisons between the different plants. The data so obtained show that utilization of the wind is constant for /329
the Lykkegaard plants, whereas it is considerably exceeded by the F. L. S. plants of both types -- which also deviate considerably from one another.

7. How Does Output Depend Upon Rotor Diameter?

This question leads us to determine specific output. It is most desirable to refer output to the area swept by the blades. The corresponding values are listed in Table 10. It can be seen from the latter that output is apparently not a function of rotor diameter in the Lykkegaard plants. The corresponding data for the F. L. Smidth systems are much higher than these values. In addition, the theoretical specific output values from König are entered in Table 10 for comparison.

TABLE 10. SPECIFIC OUTPUT OF DANISH VENTOELECTRIC POWER PLANTS WITH 12 TO 24 m ROTOR DIAMETERS

		Type: Lykkegaard				F. L. Smidth	
Rotor diameter	m	12	14	16	18	17,5	24
Area swept	m²	113	154	202	254	240	452
Output for local supply (kWh) $v_m = 6$ m/s	I	11 017	14 994	—	19 395	25 760	—
	L	15 719	21 588	30 339	36 150	44 101	116 390
	T	28 569	30 343	—	52 670	73 122	—
Specific output kWh/m²	I	97,5	97,0	—	76,5	107,9	—
	L	139,2	140,1	150,0	142,4	183,6	257,8
	T	251	197	—	208	304	—
Theoretical output, from König kWh	$c_l = 0,2$	27 800	37 800	51 400	62 300	—	—
	$c_l = 0,3$	41 600	56 500	75 800	93 500	88 500	166 000
Theoretical specific output kWh/m²	$c_l = 0,2$	245	—	—	—	—	—
	$c_l = 0,3$	368	—	—	—	—	—

Conclusion

This ends the general evaluation of output data obtained from the 83 Danish ventoelectric power plants which were studied with regard to the questions formulated at the beginning. These results, obtained from actual operation, should provide important information to serve as the basis for the planning and design of ventoelectric power plants and should thus contribute to solving the problem of the economic utilization of wind power and its rational organization -- in terms of the national economy -- within the scope of the overall energy industry.

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